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Identifying and Modelling the Dynamic Behaviour of Load Carriage Systems

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Summary

This paper describes a UK MOD funded research project that aims to identify mathematical models for the dynamic behaviour of backpack suspensions. A test-rig is described which can be used to collect the dynamic data required, and the processing of the data is briefly discussed. The resulting pack suspension models can be combined with a human locomotion model, and used to study the effects of design changes that alter pack dynamics.

Introduction

Current backpack designs have evolved through a process of trial and error. In other words, new designs have been based on previous experience and the designer's judgement, rather than being based on theoretical analysis. Each design iteration has been tested using human trials and, as a result, design evolution has been slow and costly.

In engineering design, theoretical analysis and computer modelling have long been used to obtain better designs with a minimum of physical prototyping. Most of the design iterations for an engineering product are undertaken using virtual prototypes (computer models). Although the advantages of such an approach are clear, it is difficult to apply to backpack design because textile products are inherently less predictable and more difficult to analyse theoretically than normal engineering products. To compound the problem, there is considerable variation amongst the soldiers that use the pack, and in the contents of the pack.

Despite these difficulties, there has been research activity in this area. For example, theoretical analysis has been applied to load distribution within the pack and the calculation of the corresponding mass properties [1]. Static biomechanical models have also been developed to calculate the unknown strap and interface forces given that there are sufficient measured forces and geometric parameters to make the problem statically determinate [2]. This paper describes a research project being undertaken for the UK MoD, the aim of which is to identify mathematical models for the dynamic behaviour of backpack suspensions. These models will be used to predict the effects of design changes, which alter the suspension characteristics.

A test-rig has been developed to identify dynamic suspension models for existing packs. The test-rig has similarities with the load carriage simulator at Queens University in Kingston, Canada [3]. The Queens facility has been developed to provide a means of testing pack designs prior to human trials, and relies on empirical correlation's between test-rig measurements and human trial data. Conversely, the authors' test-rig has been designed to collect the dynamic data required to identify mathematical pack suspension models.

Modelling pack dynamics and human locomotion

As explained above, the aim of the authors' work is to develop computer models that allow the pack designer to study the effects of different pack dynamics on locomotion performance. In this context, the general modelling concept is as follows.

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Sub-Models:
pack suspension model
human locomotion model

Model Inputs:
gait data
anthropometric data
mass properties

Model Outputs:
pack forces exerted on body
relative motion between pack and body
soldier's joint loads
soldier's energy consumption

Initially, the authors are studying vertical pack dynamics only, which are the most important for regular marching. If the results of this work are successful, then a full 3-D study will be considered. The requirements of a vertical model can be understood by considering the schematic shown in Figure 1. The pack and torso are represented by masses m_P and m_T respectively, and are connected by the pack suspension model. The latter will be some non-linear function of the relative motion between pack and torso (z and $\dot{z}$) that returns the net vertical force between pack and torso (F_{PAC}). The locomotion model is a function of the gait data and the force required to support the torso (F_{LEGS}). If the soldier's joint loads are required, then the locomotion model would have to be anthropomorphic. If all that is needed is an estimate of energy consumption, then a black-box model would suffice.

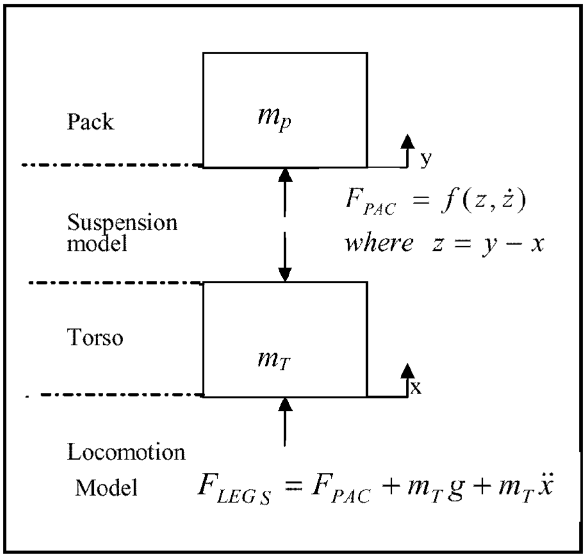

Figure 1. Model Schematic for Vertical Pack Dynamics

The main subject of this paper is the identification of the F_{PAC} function for existing packs. This requires the measurement of F_{PAC}, z and $\dot{z}$, under varying experimental conditions and for different packs, and also the identification of the corresponding mathematical pack suspension models.

Test-rig design

To identify the F_{PAC} function for an existing pack, it is necessary to measure F_{LEG}, z and $\dot{z}$ under varying experimental conditions. The test-rig developed for this purpose consists of a mannequin mounted on a hydraulic ram and equipped with appropriate instrumentation (Figures 2 & 3).

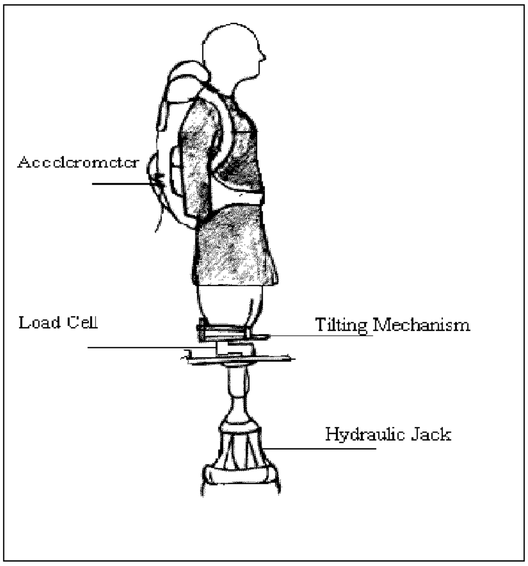

Figure 2. Schematic of Load Carriage Rig

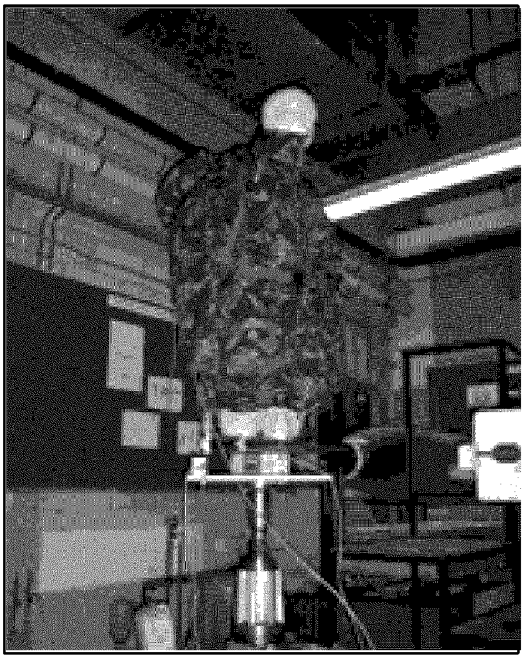

Figure 3. Photo of Load Carriage Rig

The mannequin is built on a steel frame using three times the amount of fibreglass found in a display mannequin. This reinforced construction has been used to withstand the expected dynamic loads. The steel frame allows for direct attachment to a mounting plate. The mannequin is covered in an orthotic-prosthetic material (Bocklite), to mimic human tissue.

The mannequin is mounted on a tilting assembly which allows it to adopt an angle of forward lean appropriate to the load being carried. This assembly sits on top of a load cell which measures the vertical load supporting the mannequin, (F_{LEGS}). The entire arrangement is mounted on the hydraulic ram which provides the required cyclic vertical motion.

The vertical motion of the mannequin is measured by a displacement transducer that is an integral part of the hydraulic ram. The vertical motion of the pack is measured by an accelerometer attached to the rucksack.

Test-data processing

With the mannequin being moved sinusoidally, the instrumentation allows the capture of the load supporting the mannequin (F_{LEGS}), the displacement of the mannequin (x), and the acceleration of the pack ($\ddot{y}$). The latter is integrated to give the displacement of the pack (y), and thus the relative displacement ($z = y - x$). Knowing the masses and accelerations of the pack and mannequin, the pack force can be obtained from Newton's II law as follows:

$$F_{PAC} = F_{LEGS} - m_T g - m_T \ddot{x} = m_P \ddot{y} + m_P g$$

Note that this gives two independent measures of F_{PAC}.

This quasi-sinusoidal data is then processed to obtain the amplitudes of z and F_{PAC}, and the phase difference between them. This is repeated over a range of frequencies and amplitudes, providing a database of frequency response data. By considering only their fundamental components, we can say

$$z = \hat{Z} \sin(\omega t)$$

and $$F_{PAC} = \hat{F}_{PAC} \sin(\omega t + \phi)$$

By curve fitting the frequency response data, relationships for the amplitude ($\hat{F}_{PAC}$) and phase (ϕ) of the pack force can be obtained, which have the following general form:

$$\hat{F}_{PAC} = fn(\omega, \hat{Z})$$
$$\phi = fn(\omega, \hat{Z})$$

Finally, these frequency domain relationships can be used to establish the required time domain function for pack force, $F_{PAC} = fn(z, \dot{z})$. This is the pack suspension model that can be used, along with a human locomotion model, to assess the effects of altering pack dynamics.

Conclusions

A test-rig has been designed to measure the dynamic behaviour of backpacks and thereby identify mathematical pack suspension models. Such models can then be used, along with a human locomotion model, to predict the effects of design changes which alter the suspension characteristics. The long-term aim of this work, and other modelling work like it, is to reduce the reliance on human trials in the design evolution of future backpacks. The return would be better designs, produced more quickly and at lower cost.

Acknowledgements

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